INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

SMR.704 - 25

Workshop on Materials Science and Physics of Non Conventional Energy Sources

(30 August - 17 September 1993)

"Activities on Alternative PV Materials & Devices at the Portici Research Center"

M. Garozzo
ENEA
Centro Richerche Fotovoltaiche
Dipt. Alternative Rinnovabili e Risparmio Energetico
via Vecchio Macello
80055 Portici, Naples
Italy

These are preliminary lecture notes, intended only for distribution to participants.

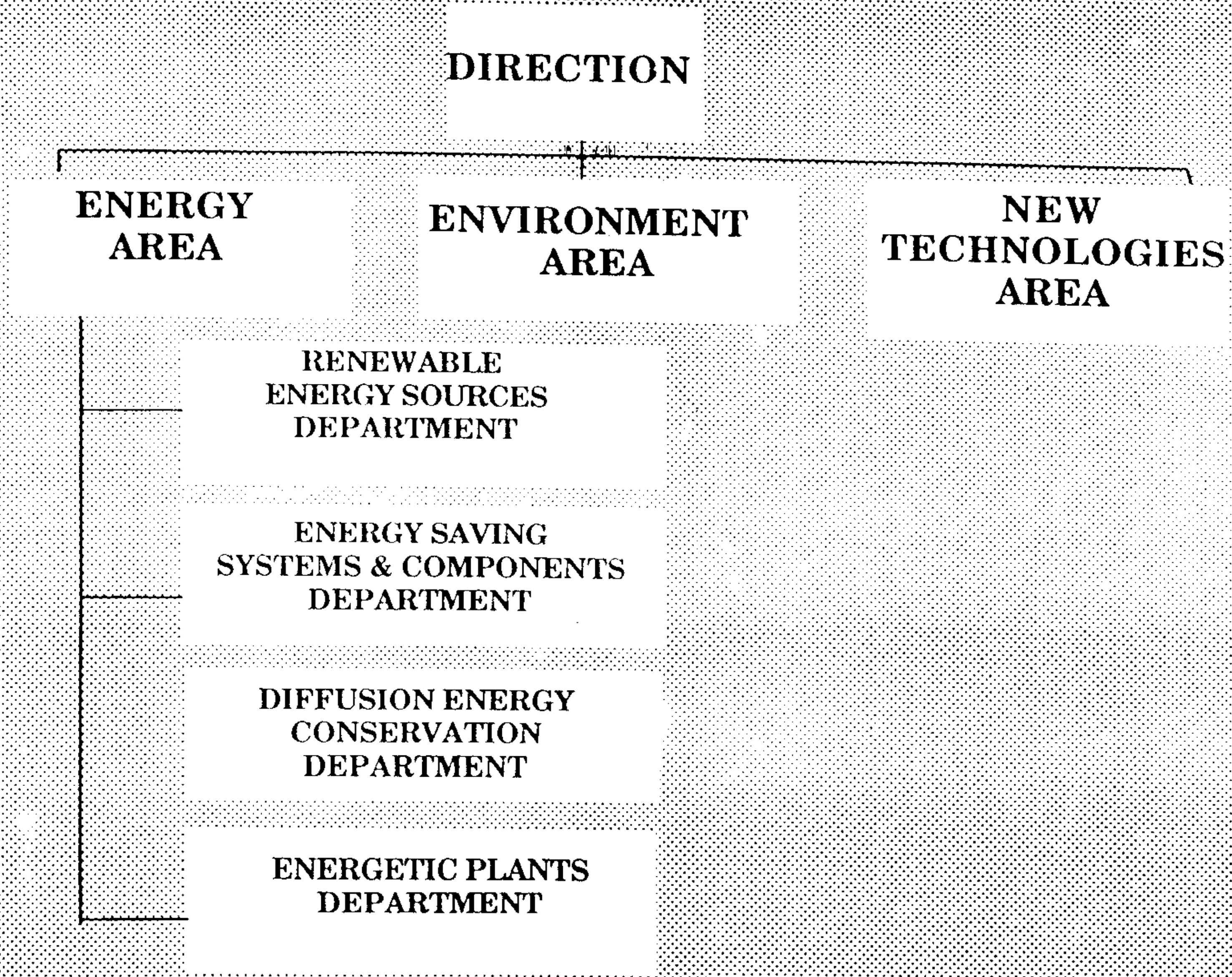
ACTIVITIES ON ALTERNATIVE PV MATERIALS & DEVICES AT THE PORTICI RESEARCH CENTER

M. GAROZZO

ENEA

THE ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND THE ENVIRONMENT

ENEA ORGANIZATION



Renewable Energy Sources Department
Project investment 1982- 1992
(billion lire)

Photovoltaic	153
Wind energy	61
Biomass and waste	42
TOTAL	256

ENEA PHOTOVOLTAIC PROGRAM

INVESTMENTS 1979-1992

ACTIVITIES	BILLION OF LIRE	
◊ R&D	110	
• [illegible] activities		104
• Outdoor activities		6
◊ INDUSTRIAL PROMOTION	18	
◊ DEMONSTRATION	25	
• ENEA Plants		22
• Other Plants		3
TOTAL	153	

ENEA PHOTOVOLTAIC PROGRAM

- ◊ RESEARCH AND DEVELOPMENT
  - MATERIALS AND DEVICES
  - BOS COMPONENTS AND SYSTEMS
- ◊ INDUSTRIAL PROMOTION
  - NEW PRODUCTION PROCESSES
- ◊ DEMONSTRATION
  - NEW APPLICATIONS

ENEA PHOTOVOLTAIC PROGRAM

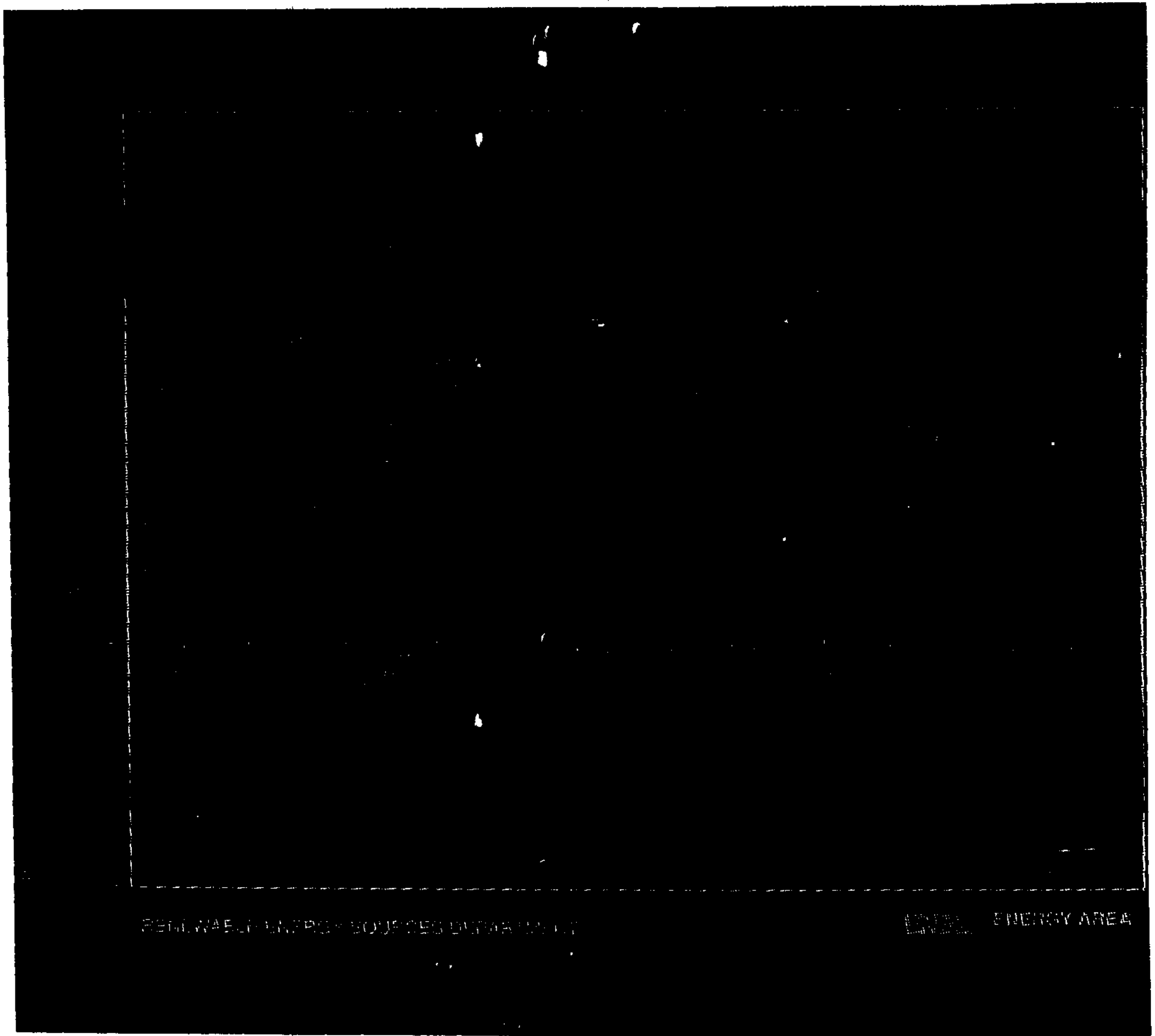
STRATEGICAL GOAL

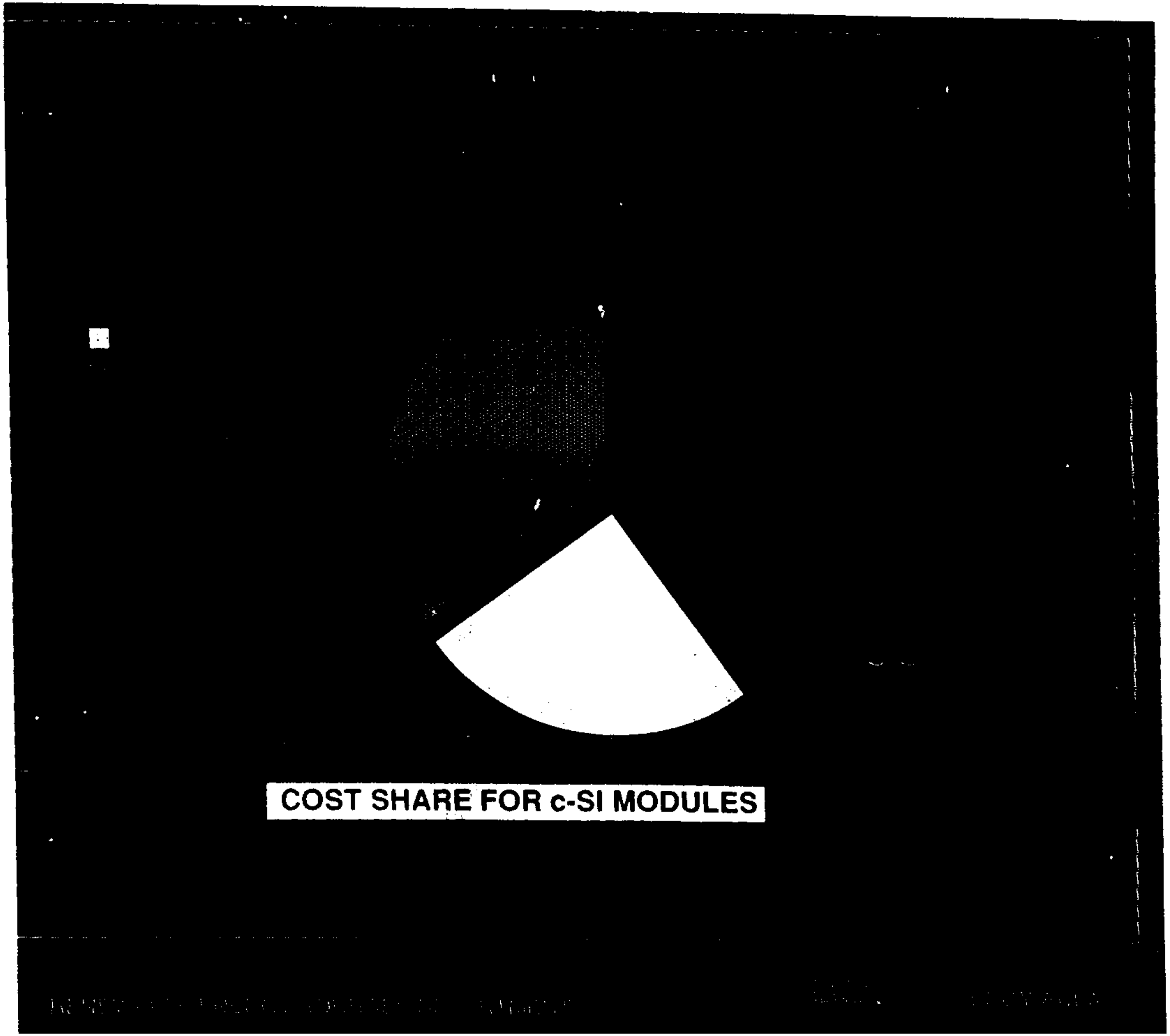
contribute to technical development and cost effectiveness attainement of photovoltaic technology for electrical energy bulk production

STRATEGY

- *Short term* :
  development of solar grade crystalline silicon photovoltaic cells

- *Long term:*
  development of thin film single junction and multijunction devices


RENEWABLE ENERGY SOURCES
ENERGY AREA


COST SHARE FOR c-SI MODULES

- USING LESS MATERIAL (decreasing the cell thickness from the current 350 - 450 μm to 100 - 150 μm)
- USING SOLAR GRADE MATERIAL, cheaper than the electronic grade one
- INCREASING THE MODULE CONVERSION EFFICIENCY
- VERY LARGE PRODUCTION VOLUMES (> 10 MWp/Yr)

NEVERTHELESS, EVEN IF A MODULE COST OF $ 2-2.5 Wp SEEMS TO BE ACHIEVABLE WITH c-Si TECHNOLOGY IN THE NEXT YEARS, A COST EFFECTIVE ENERGY MASS PRODUCTION NEEDS MODULE COST LOWER THAN $ 1 Wp WITH HIGH CONVERSION EFFICIENCY AND LIFETIME.

c-Si TECHNOLOGY DOES NOT SEEM TO ALLOW THE ACHIEVEMENT OF SUCH A GOAL, THEREFORE WE NEED TO INVESTIGATE NEW MATERIALS AND TECHNOLOGIES

MANY ALTERNATIVE SEMICONDUCTOR MATERIALS APPEAR AS VERY PROMISING FOR PV TECHNOLOGY.

THESE MATERIALS HAVE TO BE SUITABLE FOR THE THIN FILM TECHNOLOGY, WHICH SEEMS TO BE THE ONLY TECHNOLOGY FOR REACHING, IN A MEDIUM-LONG TERM PERSPECTIVE, THE ULTIMATE COST GOAL FOR LARGE MASS ENERGY PRODUCTION.

MAIN ADVANTAGES OF THE THIN FILM TECHNOLOGY

- STRONG REDUCTION OF THE EMPLOYED MATERIALS (THICKNESS <1 $m\mu$)
  --> LOW MATERIAL COSTS
- LOW DEPOSITION TEMPERATURE ALLOWING A VERY LOW ENERGY PAYBACK TIME
  (NO INTER DIFFUSION PHENOMENA -> MULTI-LAYER STRUCTURES)
- ON-LINE PROCESS IN THE MODULES PRODUCTION PROCESS
  --> HIGH PRODUCTION RATES
  --> QUICK CAPITAL COST RECOVERY
  --> BIG ROLE PLAYED BY THE PRODUCTION SCALE FACTOR ON THE FINAL MODULE COST
- CAPABILITY OF OBTAINING INTEGRATED MONOLITHIC MODULES (NO CELL MOUNTING AND INTERCONNECTION)
  --> LOW MAN POWER COSTS
  --> OPTIMISATION OF THE MODULE I-V CHARACTERISTICS ACCORDING TO THE REQUESTED APPLICATION, KEEPING CONSTANT THE OUTPUT POWER (ONE OR MORE PROCESS STEPS CAN BE MODIFIEDVIA COMPUTER, WITHOUT ANY HARDWARE CHANGE ON THE PRODUCTION LINE)

THE NEW MATERIALS

TO DIRECTLY CONVERT SOLAR ENERGY THE OPTICAL AND ELECTRICAL PROPERTIES OF SEMICONDUCTOR MATERIALS MUST SATISFY CERTAIN REQUIREMENTS:

- AN INTERNAL POTENTIAL BARRIER HAS TO BE REALIZED (p-n or p-i-n JUNCTIONS, HETEROJUNCTION).
- A GOOD MATCHING BETWEEN THE SOLAR SPECTRUM (BLACK-BODY RADIATION AT T=6000 °K) AND THE SEMICONDUCTOR ENERGY GAP, Eg, IS REQUIRED.
  (Eg SHOWS A MAXIMUM AT 1.4 eV).

PARTICULAR EMPHASIS HAS PAID TO THOSE THAT:

- CAN ABSORB LIGHT IN SMALL THICKNESSES (DIRECT Eg)
- CAN BE DEPOSITED AS THIN FILMS ON LARGE AREAS, STILL KEEPING OPTICAL AND ELECTRICAL PROPERTIES GOOD ENOUGH FOR PV CONVERSION.

THE MOST INTERESTING SEMICONDUCTORS FOR THE THIN FILM TECHNOLOGY ARE:

- HYDROGENATED AMORPHOUS SILICON (a-Si:H)
- POLYCRYSTALLINE COMPOUNDS, LIKE $CuInSe_2$ (CIS) AND CdTe.

ENEA PHOTOVOLTAIC PROGRAM

INTERNAL RESEARCH AND DEVELOPMENT ACTIVITIES

- MATERIALS AND DEVICES

- Development of innovative technologies and processes for fabrication of high efficiency crystalline silicon cells
- Development of fabrication technology of amorphous silicon integrated modules (100-1000 sq cm) and realization of a pilot plant
- Development of fabrication technologies of poly-crystalline thin film cells (CIS)
- Development of fabrication technologies of innovative very high efficiency Gallium-Arsenide cells

ENEA PHOTOVOLTAIC PROGRAM
ENEA LABORATORIES AND ACTIVITIES

ENEA CASACCIA RESEARCH CENTRE

- Crystalline silicon technology

ENEA PORTICI RESEARCH CENTRE

- Thin film technology
  - Amorphous Silicon
  - Copper Indium Diselenide
  - Gallium Arsenide

ENEA MONTE AQUILONE RESEARCH CENTRE

- Demonstration plant operation and testing
- Balance of system components testing

ENEA PHOTOVOLTAIC PROGRAM
CRYSTALLINE SILICON

MAIN TECHNOLOGIES:

- Emitter Realization (POCl3 Diffusion, SIO2 Passivation)
- Laser Grooving Technique (Selective Emitter)
- Electrical and Optical Confinement Techniques
- A.R. Coating
- Clean Room Photolithography
- Dark & Light I-V, absolute spectral response
- Three wavelengths LBIC

ENEA PHOTOVOLTAIC PROGRAM
MAIN RESULTS ALREADY ACHIEVED (1)

MATERIALS AND DEVICES

CRYSTALLINE SILICON

- set up of principal techniques for characterization of materials and devices
- fabrication of thin (200 micron), large area (100 cm2) crystalline silicon cells with high efficiency thanks to innovative and sophisticated diffusion and contacting techniques and the utilization of incident light confinement techniques.

THE ACTIVITIES ARE CARRIED OUT IN CLOSE CONNECTION WITH THE ITALIAN PV INDUSTRY AND ALSO IN THE FRAMEWORK OF AN EUROPEAN PROGRAMME, PARTIALLY SUPPORTED BY THE E.C. (JOULE PROJECT)

THE ENEA R&D ACTIVITIES

- TO REDUCE THE COST OF THE PV kWh, ENEA IS CARRYING OUT AN AMBITIOUS MULTI-YEAR PROGRAMME, RANGING FROM MATERIALS TO LARGE PV PLANTS
- THE MAJOR PART OF THE ENEA R§D ACTIVITIES HAS BEEN CONCENTRATED IN THE NEW PHOTOVOLTAIC RESEARCH CENTER (CRIF) AT PORTICI (20 Km SOUTH OF NAPLES), RECENTLY OPENED (NOVEMBER 1990)
- ALL THE MAIN NEW PV TECHNOLOGIES (THIN FILM CELLS AND MODULES) ARE INVESTIGATED IN THIS CENTER
- THE ACTIVITIES ON PV SYSTEMS ARE CARRIED OUT IN THE DELPHOS (APULIA) EXPERIMENTAL AREA, WHERE THE LARGEST EUROPEAN PLANT (600 kWp) IS OPERATING
- THE RESEARCH ON C-SILICON IS PERFORMED IN CASACCIA (ROME), IN CLOSE COLLABORATION WITH EUROSOLARE

ENEA
Energy Area

ENEA PORTICI
PHOTOVOLTAIC RESEARCH CENTRE

TOTAL INVOLVED AREA	27,000 m2
COVERED AREA	5,000 m2
BUILDING TOTAL VOLUME	60,000 m3
LABORATORIES AND FACILITIES	12,000 m2
PERMANENT STAFF	
- TODAY	70
- 1994	150

PORTICI PHOTOVOLTAIC RESEARCH CENTRE

MAIN GOALS

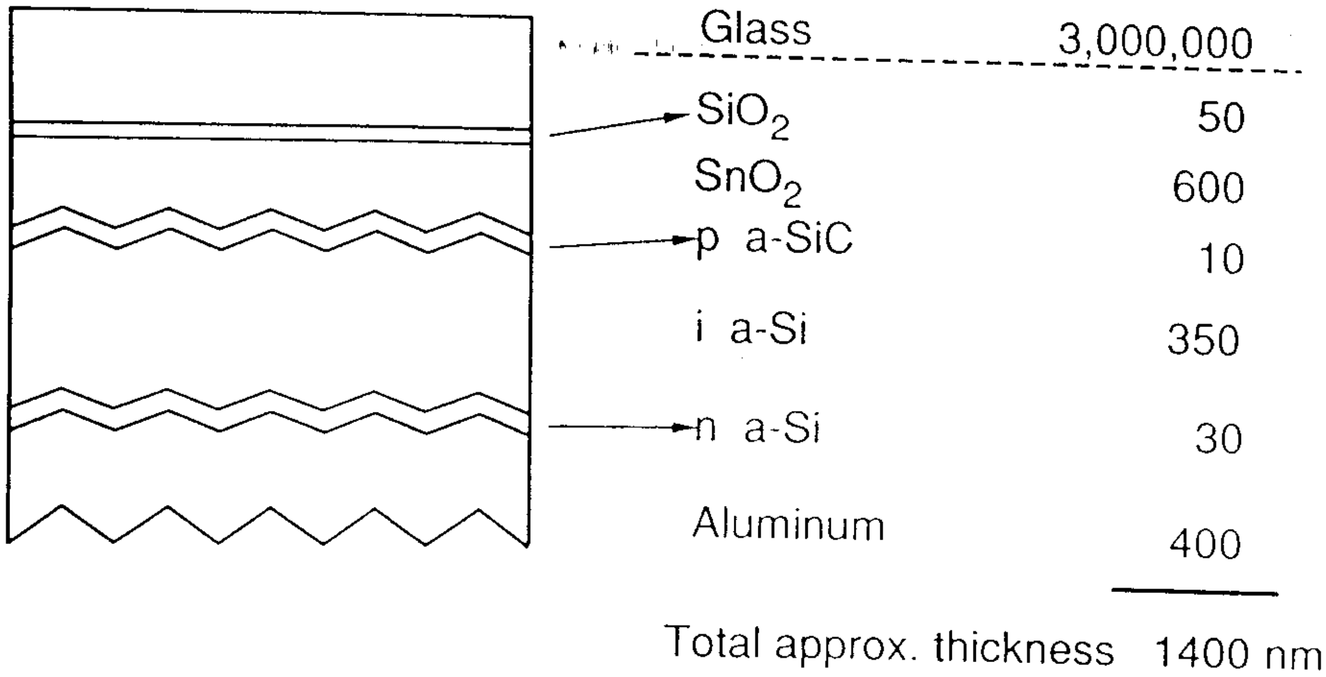
- DEVELOPMENT OF PHOTOVOLTAIC TECHNOLOGY FOR ENERGY APPLICATIONS:

  -Re[illegible] and Development on innovative semiconductor m[illegible]
  -Re[illegible] and Development of Cells and Modules
  -Re[illegible] of pre-pilot plants for modules construction

- Co[illegible] transfer to the National Photovoltaic Industry

- App[illegible] the fields of optoelectronics and Integrated ele[illegible] a large scale

- Tes[illegible]ovoltaic plants and demonstrative applications (De[illegible]anfredonia)

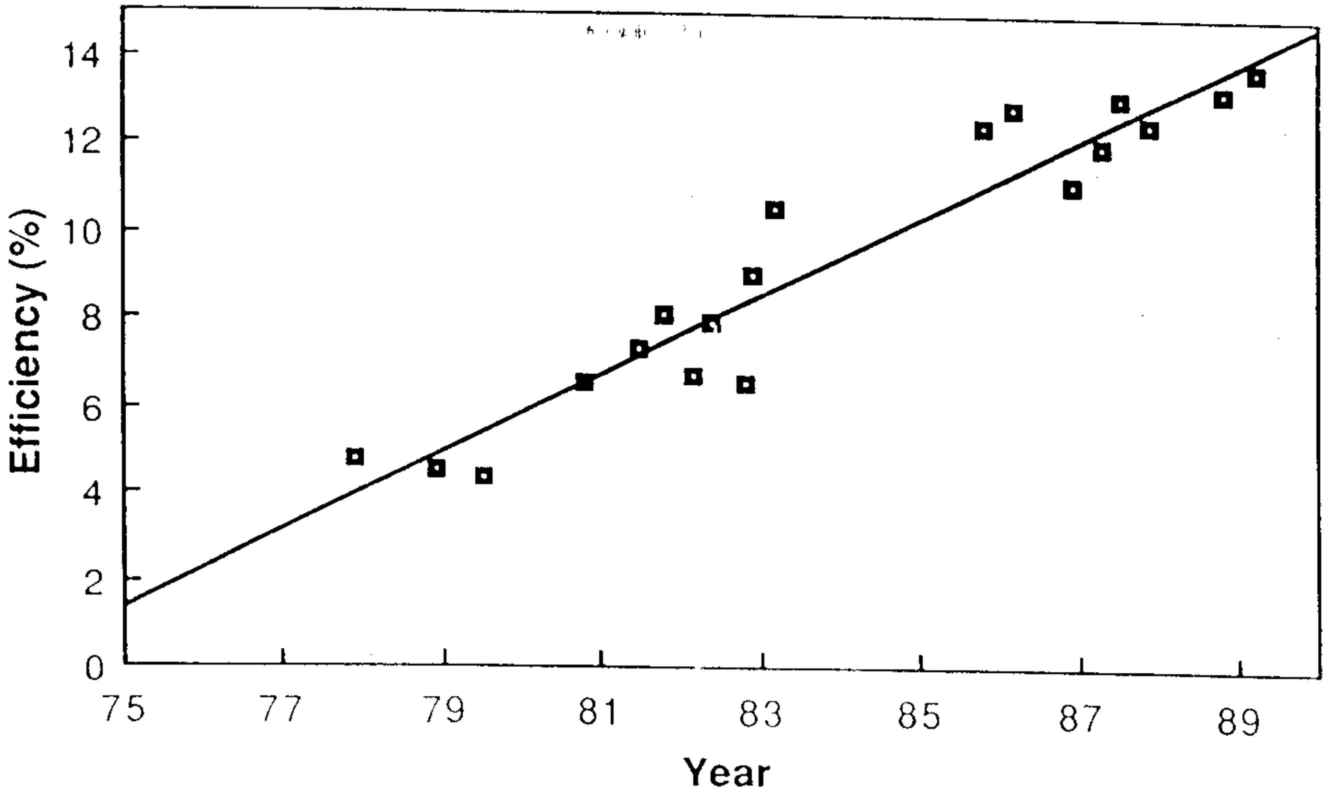


SCHEME OF A a-Si-H SINGLE-JUNCTION SOLAR CELL (Layers are not reported in scale)

ENEA ENERGY AREA

a-Si:H SOLAR CELLS

- THE FIRST a-Si:H SOLAR CELL (1976) USED SCHOTTKY BARRIERS WITH η = 5-6%: LOW Ld DID NOT ALLOW GOOD CARRIER COLLECTION.
- AN ELECTRICAL FIELD IS NEEDED WHERE THE CARRIER GENERATION OCCURS.
- p-i-n JUNCTIONS ARE EMPLOYED, WHERE "i" IS THE UNDOPED LAYER WHERE THE MAJOR PART OF THE CARRIERS IS GENERATED AND SWEPT OUT BY THE ELECTRICAL FIELD CREATED BY MEANS OF THE n-DOPED AND p-DOPED LAYERS.
- TO ACHIEVE THE BEST TRADE-OFF BETWEEN A COMPLETE LIGHT ABSORPTION AND AN EFFECTIVE CARRIER COLLECTION, THIN i-LAYERS ARE COMMONLY USED TOGETHER WITH TEXTURING FOR AN EFFICIENT LIGHT TRAPPING.
- THE FRONT CONTACT IS MADE OF A TRANSPARENT CONDUCTIVE OXIDE (TCO), USUALLY SnO_2 AND IS TEXTURED FOR LIGHT TRAPPING.
- i LAYER IS VERY THIN TO ENSURE A HIGH ELECTRIC FIELD (> 20kV/cm).
- ALUMINUM BACK CONTACT SERVES AS A REFLECTOR FOR LIGHT TRAPPING.
- p^+ LAYER CONSISTS OF A-SIC:H ALLOY TO REDUCE OPTICAL ABSORPTION IN THIS DEAD LAYER.



LEARNING CURVE FOR a-Si:H SMALL AREA CELLS

ENEA ENERGY AREA

a-Si:H SOLAR CELLS

- A VARIETY OF SUBSTRATES MAY BE USED TO TAKE ADVANTAGE OF THE LOW DEPOSITION TEMPERATURE FOR a-SI (250 °C).
- THE MOST COMMON SUBSTRATE IS GLASS, BUT a-Si:H CELLS CAN BE ALSO DEPOSITED ON FLEXIBLE SUBSTRATES LIKE STEEL OR POLYMER FOILS, AND ON CURVED SUBSTRATES.
- THIS VARIETY OF SUBSTRATE TYPES AND SHAPES OPENS EXTRA APPLICATIONS, AS CAR ROOFS AND THE POWERING OF SOLAR AIRPLANES.
- AT LABORATORY LEVEL, CELL EFFICIENCY HAS BEEN GROWING STEADILY UP TO 13.8% FOR 1 cm^2 AREA CELL ALSO EMPLOYING MULTIJUNCTION STRUCTURES.
- THIS APPROACH IS FOLLOWED ALSO TO OVERCOME SOME INTRINSIC STABILITY PROBLEMS, WHICH SEEM TO BE THE MAJOR LIMIT FOR THE DIFFUSION OF a-Si:H MODULES IN MASSIVE ENERGY PRODUCTION.

a-Si:H THIN FILM TECHNOLOGY

- ELECTRONIC QUALITY a-Si:H IS OBTAINED BY THE GLOW-DISCHARGE (GD) DEPOSITION TECHNIQUE (ON-LINE PROCESS ON AREA UP TO 1 m^2).
- GD RELIES ON THE CREATION OF A LOW IONIZED PLASMA OBTAINED BY AN ELECTRICAL DISCHARGE IN PROPER ATMOSPHERE.
- THE GROWTH MECHANISM CONSISTS IN THE MIGRATION OF NEUTRAL SPECIES THROUGHOUT THE DEPOSITION CHAMBER UNTIL THEY IMPINGE ON THE SUBSTRATE.
- SiH_4 FOR INTRINSIC MATERIAL; PH_3 FOR n-DOPING; B_2H_6 FOR p-DOPING
- SILICON BASED ALLOYS (SiC, SiN, SiGe) CAN BE OBTAINED.
- FEASIBILITY OF DEPOSITING SEVERAL SEMICONDUCTORS ON SUBSTRATES DIFFERING FROM ONE ANOTHER IN MATERIAL AND SHAPE.
- a-Si:H IS EMPLOYED IN MANY ELECTRONIC AND OPTOELECTRONIC DEVICES: TODAY PHOTOCOPIERS, FLAT PANEL DISPLAYS, MASS STORAGE MEMORIES BASED ON a-Si:H ARE COMMERCIALLY AVAILABLE.

a-Si:H PV MODULES

- THE a-Si:H TECHNOLOGY ALLOWS THE PRODUCTION OF ENTIRE MODULES, WITH AREAS UP TO ONE SQUARE METER.
- WHEREAS SINGLE-CRYSTAL CELLS ARE ASSEMBLED INDIVIDUALLY TO A MODULE, a-Si:H MODULES ARE PARTITIONED INTO INDIVIDUAL CELLS DEPENDING ON THEIR APPLICATION.
- THE INTEGRATED MONOLITHIC MODULES ARE CURRENTLY FABRICATED BY EMPLOYING TECHNOLOGIES INVOLVING PREPARATION OF GLASS SUBSTRATES, GAS PHASE DEPOSITION OF TCO, GLOW DISCHARGE OF AMORPHOUS SILICON AND VACUUM EVAPORATION OR SPUTTERING OF BACK CONDUCTOR.
- THREE PATTERNING STEPS FOR SOLAR CELLS INTEGRATION ARE COMMONLY CARRIED OUT BY USING A Nd:YAG LASER, WHILE MECHANICAL AND ELECTROMECHANICAL APPROACHES ARE ALSO AVAILABLE.
- MODULES SIZE RANGES FROM 10x10 cm^2 UP TO 60x125 cm^2 WITH STABILIZED η = 5-6%.
- FUJI HAS RECENTLY REPORTED (1993) MODULES WITH STABILIZED η = 8.5%.

ENEA ENERGY AREA

a-Si:H PV MODULES

- WORLD-WIDE THERE ARE APPROXIMATELY 20 a-Si:H MODULES MANUFACTURERS (4 IN EUROPE), FOR ABOUT 1/4 OF THE TOTAL PV SHIPMENTS.

- THE MAIN APPLICATION OF a-Si:H MODULES IS IN SMALL POWER PRODUCTS, DUE TO THE LOW STABILIZED η (HIGH B.O.S COSTS FOR LARGE POWER PLANTS).

- THE MARKET GROWTH IS CORRELATED TO THE NEED OF HIGHER STABILIZED POWER OUTPUTS.

- IN THIS AIM, THE CRITICAL RESEARCH ISSUES INCLUDE:

  * REDUCING OR ELIMINATING METASTABILITIES;
  * IMPROVING LOW AND HIGH Eg MATERIALS IN MULTIJUNCTIONS DEVICES;
  * UNDERSTANDING AND CONTROLLING THE USED DEPOSITION PROCESSES;
  * MODELING AND DEVELOPING DEVICE ENGINEERING TAKING ALSO INTO ACCOUNT THE INTERFACE PHENO IENA.

SHOULD THESE RESEARCH ACTIVITIES BE SUCCESSFUL, A TREMENDOUS COST REDUCTION WOULD BE POSSIBLE:
BY A FULLY AUTOMATED PRODUCTION AT 10 MWp/Yr, COUPLED WITH A 9 -10 % STABILIZED MODULE EFFICIENCY, A COST OF FAR BELOW 1 $/Wp IS ACHIEVABLE.

R & D ACTIVITIES ON α-Si at the PORTICI RESEARCH CENTER

ACTIVITY LINES

- To develope high efficiency single- and multi-junction α–Si cells and 100 cm^2 integrated modules
- To study the intrinsic (material) and extrinsic (interfaces) instability phenomena
- To develope low-cost 1000 cm^2 module fabrication processes

SOME OF THESE RESEARCH ACTIVITIES ARE CARRIED OUT IN COLLABORATION WITH SIEMENS IN THE FRAMEWORK OF THE JOULE II EUROPEAN PROJECT

R & D ACTIVITIES ON α-Si at the PORTICI RESEARCH CENTER

MAIN TECHNOLOGICAL FACILITIES:

- 3 Chamber + Load Lock Glow Discharge Apparatus (100 cm^2)
- 3 Chamber in-line Glow Discharge Apparatus (100 cm^2)
- Single Chamber 100 cm^2 Glow Discharge
- Vertical Single Chamber Glow Discharge 1000 cm^2 (2 Substrates)
- Spray Pyrolysis TCO (SnO_2:F) Deposition System (100 cm^2)
- Vacuum Deposition Systems for Metals and Oxides
- Computerized Laser Scribing Technique for Integrated 1000 cm^2 Modules
- Screen Printing Technique for Integrated Modules

R & D ACTIVITIES ON α-Si at the PORTICI RESEARCH CENTER

MAIN CHARACTERIZATION FACILITIES:

- SEM WITH X-RAY MICROPROBE AND EBIC TECHNIQUE
- RAMAN LASER, IR and FT-IR SPECTROSCOPIES
- UV-VIS. ABSORBANCE, SPECULAR AND DIFFUSE REFLECTANCE
- C-V MEASUREMENTS vs. Ω AND T
- SPECTRAL PHOTOCONDUCIVITY
- PHOTOTHERMAL DEFLECTION SPECTROSCOPY
- STEADY STATE PHOTOCURRIER GRATING (SSPG) TECHNIQUE

R & D ACTIVITIES ON α-Si at the PORTICI RESEARCH CENTER

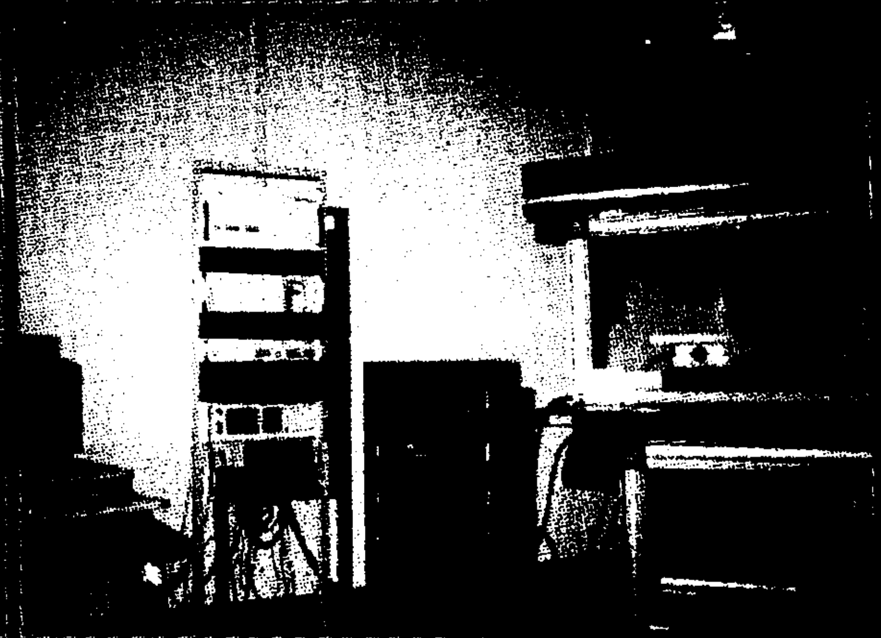
MAIN CHARACTERIZATION FACILITIES:

- HALL EFFECT MEASUREMENTS (carrier concentration and mobility) FOR 20 °K ≤ T ≤ 400°K
- COMPUTERIZED ABSOLUTE INT. &EXT. SPECTRAL RESPONSE UP TO 15X15 cm^2 AREA
- CLASS A CW AND PULSED SOLAR SIMULATORS
- CELL MODELLING

ENEA PHOTOVOLTAIC PROGRAM

Portici Photovoltaic Centre Experimental Facilities

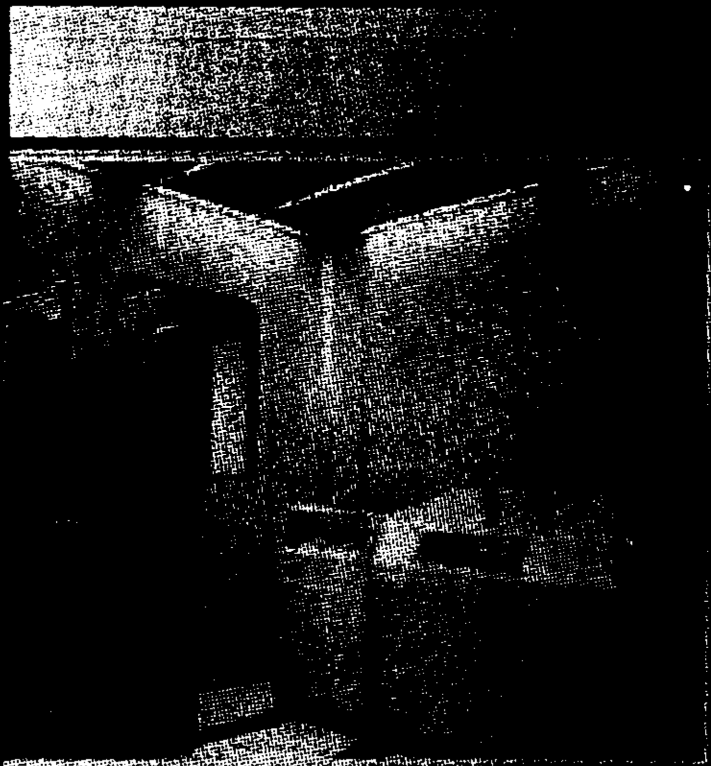
Three chamber deposition apparatus of amorphous silicon thin films by glow discharge technique



Laser scribing system fabricating amorphous silicon monolithic integrated modules (up to 1000 cm2 area)

ENEA PHOTOVOLTAIC PROGRAM

Portici Photovoltaic Centre Experimental Facilities



Photolithography technology in 100 class clean room for the fabrication of high efficiency photovoltaic cells

Raman-Laser spectrometry facility. Front view showing the sample holder and the monocromator inlet slide

MAIN RESULTS ON a-Si:H

MATERIALS

THREE-CHAMBER LOAD-LOCK PA-CVD APPARATUS (up to 100 cm^2)

i-layer: DoS < 10^{15} cm^{-3} — Urbach Edge = 43 meV
Photoconductivity recovery > 10^6 — L_d = 240 nm

p-and n-doped layers: state of the art quality

μ-crystalline doped layers obtained at very low RF power (no TCO and i-layer damage during the deposition)

μ-c P-doped layers:
- crystallinity percentage: 95 % — grain size = 80 Å
- conductivity = 71 S/cm — E_a = 20 meV

μ-c B-doped layers:
- crystallinity percentage: up to 75 % — grain size = 200 Å
- conductivity = 4 S/cm — E_a = 20 meV

Spray pyrolysis deposition of textured TCO (up to 100 cm^2)

F-doped SnO_2: transmittance > 85 % (600 nm) — $\rho = 10^{-3}\ \Omega$ cm

MAIN CRIF RESULTS ON a-Si:H

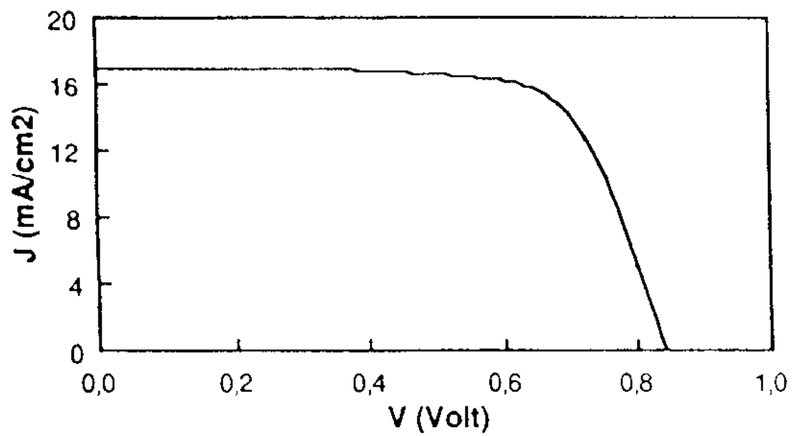
SMALL AREA SINGLE-JUNCTION CELLS

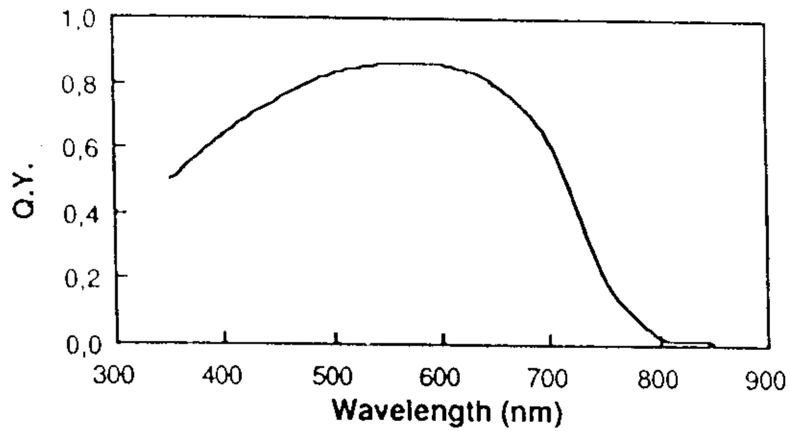
Cell structure: TCO/p-SiC:H(B)/a-Si:H/nc-Si:H(P)/Ag

active area: 1 cm^2

efficiency: 10.2 % (no optimized back reflector)

V_{oc} = 830 mV   Jsc = 17.2 mA/cm^2 F.F. = 0.72





MAIN RESULTS ON a-Si:H

SMALL AREA TANDEM-JUNCTION CELLS AND SMALL MODULES

Cell structure: Tandem pin-pin with n^+/p-SiC:H recombination layer

active area: 1 cm^2
efficiency: 8.3 % (no optimized back reflector)
V_{oc} = 1.75 V J_{sc} = 7.0 mA/cm^2 F.F. = 0.68

Module structure: (9 stripe-shaped 1 x 9 cm^2 series interconnected cells)

active area: 81 cm^2
efficiency: 7.8 % (no optimized back reflector)
V_{oc} = 6.93 V J_{sc} = 17.0 mA/cm^2 F.F. = 0.66

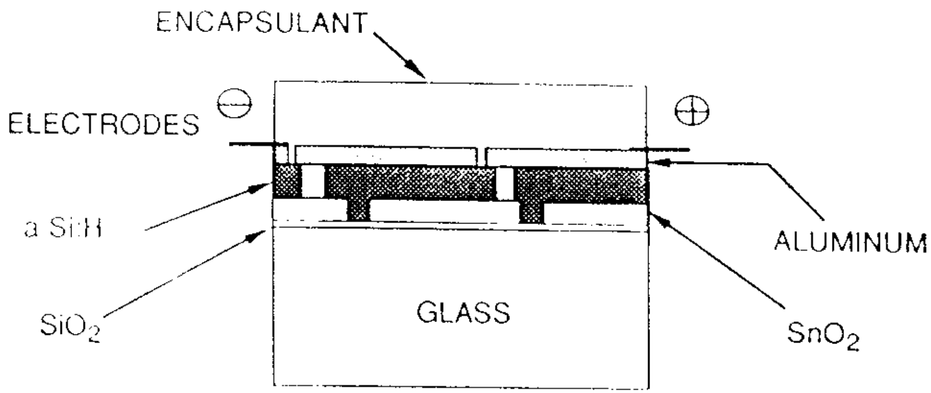
RESULTS ON a-Si:H

1000 cm^2 INTEGRATED MODULES

Cell structure: TCO/p-SiC:H(B)/a-Si:H/n-Si:H(P)/Al

Single chamber two substrates PA-CVD Nextral apparatus
Laser scribing system
Multi-target MRC sputtering equipment

30 stripe-shaped (1 cm x 30 cm) series interconnected cells
efficiency: 5.0 % (no optimized back reflector)
V_{oc} = 23.1 V J_{sc} = 12 mA/cm^2 F.F. = 0.60



SCHEMATIC CROSS SECTION OF THE a-Si:H MONOLITHIC INTEGRATED MODULE

POLYCRYSTALLINE SEMICONDUCTOR SOLAR CELLS: CIS

- **THE RESEARCH ON THESE CELLS HAS WORLD-WIDE RECEIVED A LARGER AND LARGER EFFORT SINCE BOEING (1985) AND ARCO SOLAR (1988), OBTAINED VERY INTERESTING RESULTS USING $CuInSe_2$ (CIS) AS ABSORBING MATERIAL AND CdS AS WINDOW LAYER.**
- CIS-BASED SOLAR CELLS HAVE $\eta > 15\%$.
- η FOR INTEGRATED MODULES IS 11.2% (938 cm^2) AND 10.4% (3883 cm^2).
- NO EVIDENCE HAS BEEN OBSERVED OF LONG OR SHORT TERM DEGRADATION.
- IN COMPARISON WITH c-SI OR a-Si:H, CIS IS IN THE EARLY STAGE OF MASS PRODUCTION.
- BASIC AND APPLIED RESEARCH IS REQUIRED TO GET INFORMATION ON THE FUNDAMENTAL PROCESSES DURING THE GROWTH OF THE ACTIVE MATERIAL AND ON DEVICE OPERATION.

<u>IF ITS POTENTIAL ADVANTAGES WITH RESPECT TO MANUFACTURING COST AND PERFORMANCES ARE CONSIDERED, CIS COULD BE THE OPTION FOR THE FUTURE.</u>

CIS DEPOSITION TECHNIQUES

THE BEST RESULTS: SIEMENS SOLAR AND BOEING PROCESSES.

- THE SIEMENS SOLAR APPROACH:

  SEQUENTIAL SPUTTERING DEPOSITION OF CU/IN BILAYERS (PRECURSORS)

  SELENIZATION IN H_2Se+Ar ATMOSPHERE AT 400 °C FOR ONE HOUR.

- IS SCALABLE FOR MASS PRODUCTION AND GIVES THE HIGHEST η.

- MAIN DISADVANTAGE: THE EMPLOY OF H_2Se, AN HIGHLY TOXIC GAS.

- THE BOEING PROCESS:

  THREE SOURCE EVAPORATION IN CONVENTIONAL HIGH-VACUUM SYSTEMS.

  Cu AND In FLUXES DETERMINE FILM COMPOSITION AND GROWTH RATE.

  Se FLUX IS TYPICALLY IN EXCESS.

- GOOD REPEATIBILITY AND RELIABILITY FOR LABORATORY LEVEL.

- IT DOES NOT SEEM SUITABLE FOR MASS PRODUCTION.

CIS SOLAR CELLS

SUBSTRATE: Mo-COATED GLASS.

- THE SIEMENS SOLAR DEVICE:

  BI-LAYER CIS ABSORBER: Cu-RICH (LOW ρ WITH MO) AND In-RICH (HIGH ρ).

  VERY THIN CdS LAYER (<50 nm) + THICK ZnO LAYER (TCO FOR ARC).

- THE BOEING DEVICE:

  CIS BI-LAYER AS IN SIEMENS SOLAR DEVICE.

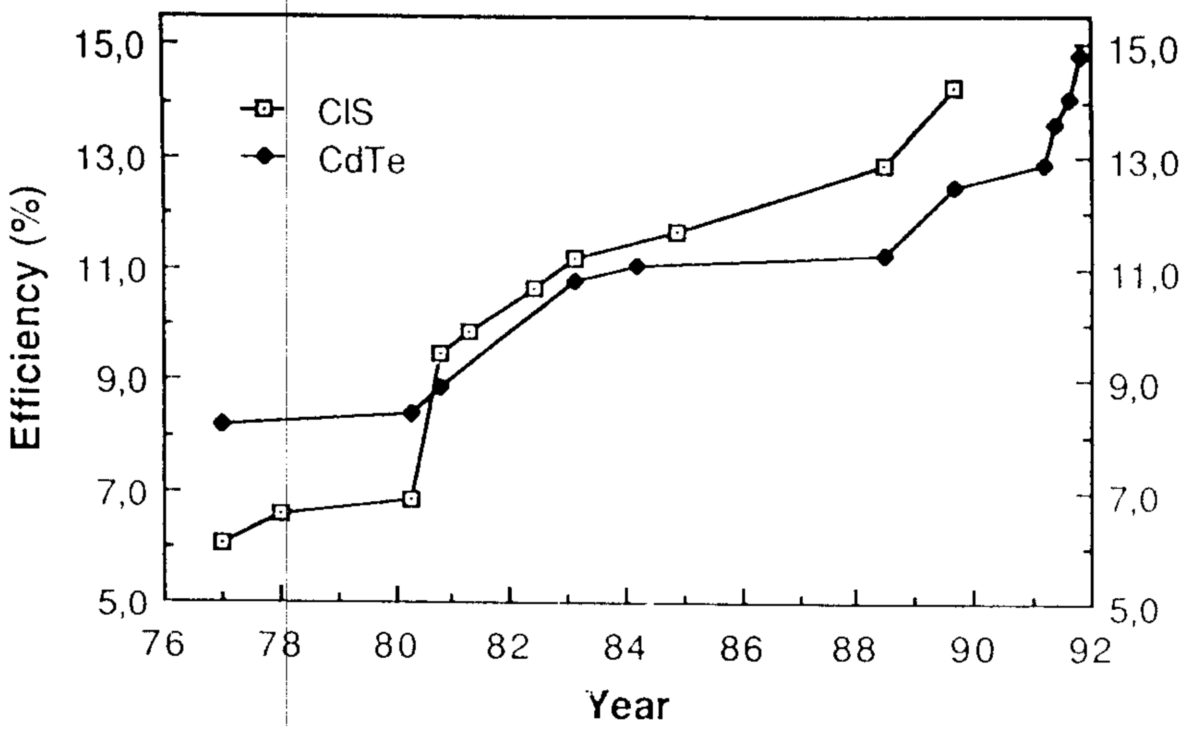
  THICK CdS BI-LAYER (LOWER: HIGH ρ; UPPER: IN-DOPED).

CIS SOLAR CELLS

MAIN PROBLEMS:

- CIS STOICHIOMETRY CONTROL
- Mo/GLASS ADHESION (DIFFERENT THERMAL EXPANSION COEFFICIENTS)
- Mo/CIS INTERFACE
- ABRUPT HETEROJUNCTION CIS/CdS
- CdS LAYER THICKNESS CONTROL ON LARGE AREAS

THE LEARNING CURVE FOR SMALL AREA CIS SOLAR CELLS SHOWS THE DRAMATIC IMPROVEMENT OBTAINED IN THE LAST FIFTEEN YEARS ON THIS MATERIAL.



LEARNING CURVE FOR CIS AND CdTe SMALL AREA SOLAR CELLS

ENEA ENERGY AREA

R & D ACTIVITIES ON CIS at the PORTICI RESEARCH CENTER

ACTIVITY LINES

- To grow CIS by sputtering and selenization (Siemens approach) for studying and optimizing morphological and electrical properties
- To grow by dipping and characterize CdS as window layer
- To fabricate solar cells and small integrated modules

THESE RESEARCH ACTIVITIES ARE CARRIED OUT IN COLLABORATION WITH MANY EUROPEAN PARTNERS IN THE FRAMEWORK OF THE JOULE II PROJECT

R & D ACTIVITIES ON CIS at the PORTICI RESEARCH CENTER

MAIN FACILITIES:

- **SPUTTERING SYSTEM FOR Cu AND In**
- **THERMAL AND SELENIZATION POST-TREATMENTS**
- **CdS GROWTH TECHNIQUES (DIPPING AND SPRAY-PYROLISIS)**
- **TRANSPORT AND STRUCTURAL PROPERTIES MEASUREMENTS**
- **DEVICES CHARACTERIZATION EQUIPMENTS**

RESULTS ON CIS

MATERIALS

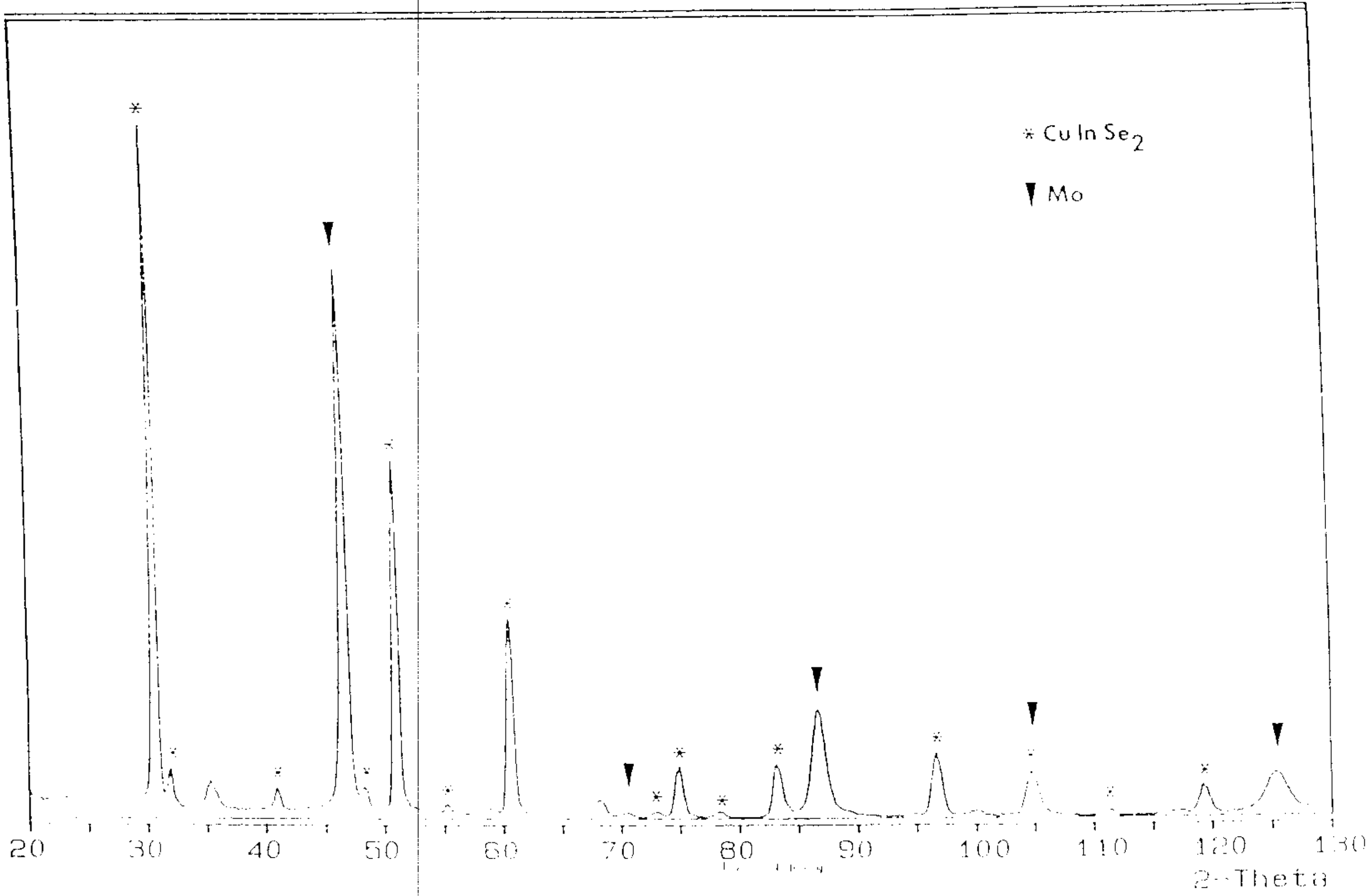
- Mo films with uniform thickness, smooth morphology and columnar structure have been sputtering deposited at T = 400 °C on glass substrates (ρ = 47 mΩ cm, film adhesion > 400 Kg/cm2)

- CIS with the proper crystallographic structure has been obtained by selenizing sputtering deposited Cu/In/Cu sandwich structures, even if some adhesion (with Mo) and uniformity problems still remain to be solved

- CdS with high transparency and good conductivity has been obtained by spray pyrolysis

- The fabrication of CIS/CdS solar cells is in progress

X-RAY DIFFRACTION SPECTRUM OF CIS FILM OBTAINED BY SELENIZATION OF Cu/In/Cu MULTI-LAYER STRUCTURE DEPOSITATED ON Mo-COATED GLASS SUBSTRATE



RENEWABLE ENERGY SOURCES DEPARTMENT

ENEA ENERGY AREA

GaAs SOLAR CELLS

- **Due to their very high conversion efficiency (>30%), GaAs solar cells are considered as very important both for space and, in a long term perspective , for terrestrial applications**

- **Two different approaches to reduce the material cost, too high for terrestrial applications, are ussually followed:**
    - **Concentration PV systems**
    - **GaAs thin film deposited on low cost substrates**

R & D ACTIVITIES ON GaAs at the PORTICI RESEARCH CENTER

ACTIVITY LINES

- Fabrication of high efficiency GaAs solar cells, deposited on GaAs substrates by MO-CVD
- Optimization of the structural and electrical properties of thin film GaAs directly grown on silicon substrates by MO-CVD
- To develope very high efficiency GaAs on Si stacked tandem solar cells

R & D ACTIVITIES ON GaAs at the PORTICI RESEARCH CENTER

MAIN FACILITIES:

- MO-CVD APPARATUS FOR GROWING GaAs and III-V COMPOUNDS
- 100 CLASS CLEAN ROOM PHOTOLITOGRAPHY
- OHMIC CONTACT AND DOUBLE A.R. COATING DEPOSITION SISTEMS
- TRANSPORT PROPERTIES MEASUREMENTS
- NON DESTRUCTIVE MICROSCOPIC DEFECTS RECOGNITION (IR EMISSION)

MAIN RESULTS ON GaAs

- Optimization of the structural and electronic properties of GaAs thin film grown on GaAs substrates by MO-CVD

- Fabrication of GaAs/GaAlAs on GaAs substrates 4 cm^2 area solar cells with a conversion efficiency larger than 23%

- Characterization of GaAs thin films grown on c-Si substrates by MO-CVD